Combined Circuit Model for a Four Quadrant Operating Luo-Converter

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***Abstract*—This work presents a combined circuit, as a new methodology, for a four-quadrant operation converter using LUO's configuration based on the model proposed by Luo and Hong Ye. The combination conjugates two different circuits, each one works for controlling two of the four quadrants or modes respectively. Additionally, this paper presents simulation results for the proposed system in order to verify its characteristics and functionality.**

***Keywords*—Luo DC/DC converter, four quadrant operation, open loop speed control for a DC motor.**

I. Introduction

DC/DC converters have been used in many industrial applications which in general performance single quadrant operation. Traditional models like buck, boost and buck-boost converters [1] have some applications oriented, mostly, to electrical power generations, photovoltaic and renewable energy sources [2] [3] [4] [5], power regulation [6] and energy storage systems [7] [8].

Luo-converters are an example of DC-DC power conversion circuits developed to perform positive to positive DC-DC voltage increasing conversion with high efficiency and near-zero output voltage and current ripples [9].

The proposed LUO circuit depends on two semiconductors used as switches which are driven by a type of PWM signals with constant switching frequency controlled independently. A 4-pole double state switch (4PDS) is used for changing from forward and reverse states.

Each mode is controlled by one switch. Each state determines the output current path [10], and to determine the direction of the rotor axis in acceleration or braking state. Multiple motor characteristics have been considered in the simulation tests, in order to the future implementation will be more reliable.

Free quadrant change is available, but is necessary to considerate events like overcurrent in the entrance circuit loop and polarity change in the capacitor. Thus, is important to determine safe conduction duty ranges to ensure system stability and integrity of the circuit elements, all depends on the characteristics of the loads. In this project, test results are presented for a DC motor load.

The difference between this work and the original proposed by Luo and Hong Ye in [11] is that it presents simulation results for the combined theoretical circuit named by them as "Circuit 3" with a little correction discussed in the next section.

II. Combined Luo-converter Model

This section describes the combined circuit proposed by Luo and Hong Ye in [11] for four quadrant operation with a small variation, instead from using a three-pole double state switch (3PDS) for the commutation, as proposed in [11] [12], to a four-pole double state switch (4PDS) will be used as shown in Fig. 2 otherwise, the proper circuit configurations will not be achieved.

The 4PDS switch defines 4 poles (A, B, C & D) and two states for each pole, it means that each pole has a common pin named A, B, C or D and each one of them has two pins, one for a first state (A1, B1, C1 or D1) and another one for a second state (A2, B2, C2 or D2) as shown in Fig. 1.

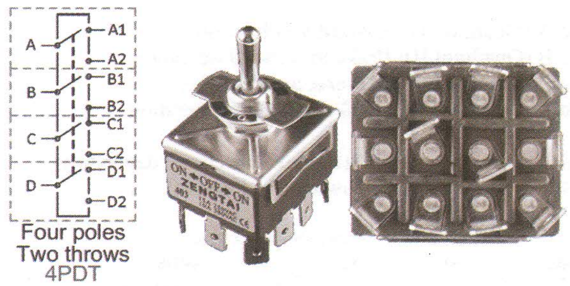


Fig. 1. Operation mode of a 4PDS switch.

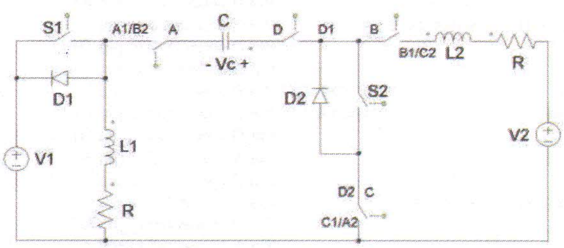


Fig. 2. Combined Luo-converter circuit topology with a 4PDS switch

V1 is the input voltage source, S1 and S2 are switches that control acceleration and braking modes, D1 and D2 are diodes, L1 is the entrance loop inductance, R is a resistance, C is a capacitor, V2 is the voltage load which represents the Electromotive Force (EMF) of a DC motor or the voltage value of a Battery in the case of a battery charge application, I_{L1} and I_{L2} are the currents which flows through inductors L1 and L2 respectively, δ is the duty cycle.

Fig. 3 and Fig. 4 show how the 4PDS works to switch from circuit 1 to circuit 2 in order to reach the Luo-converter circuit topology for operation in Quadrants I, II and III, IV respectively.

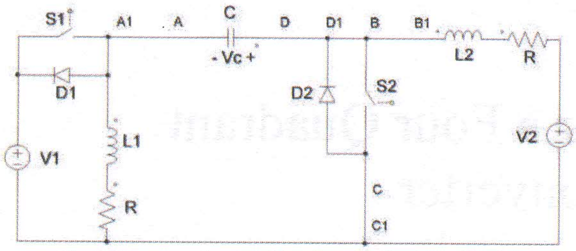


Fig. 3. Luo-converter circuit topology for Quadrants I and II

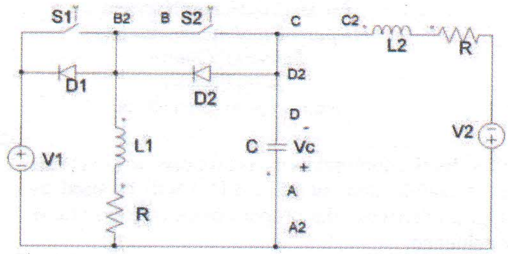


Fig. 4. Luo-converter circuit topology for Quadrants III and IV

For a comprehensive review of the functionality of this circuits, as explained by Luo and Hong Ye, refer to [11] [12].

The circuit can work in four modes or quadrants as follows:

1. Mode A (Quadrant I): Forward acceleration.
2. Mode B (Quadrant II): Brake in forward operation.
3. Mode C (Quadrant III): Reverse acceleration.
4. Mode D (Quadrant IV): Brake in reverse operation.

Table I shows the operation mode of the circuit depending on the 4PDS and the states of switches S1 and S2.

TABLE I. MODES OF OPERATION

Mode	S1	S2	4PDS
A (Quadrant I)	PWM switching	Off	Pin A connected to pin A1 Pin B connected to pin B1 Pin C connected to pin C1 Pin D connected to pin D1
B (Quadrant II)	Off	PWM switching	Pin A connected to pin A1 Pin B connected to pin B1 Pin C connected to pin C1 Pin D connected to pin D1
C (Quadrant III)	PWM switching	Off	Pin A connected to pin A2 Pin B connected to pin B2 Pin C connected to pin C2 Pin D connected to pin D2
D (Quadrant IV)	Off	PWM switching	Pin A connected to pin A2 Pin B connected to pin B2 Pin C connected to pin C2 Pin D connected to pin D2

Table II shows the considered parameters for the circuit based on calculations in [11] [12].

TABLE II. CIRCUIT PARAMETERS

Parameter	Value
V1	42 [V]
V2[a]	±14 [V]
R	0.05 [Ω]
L1 = L2	0.5 [mH]
C	20 [μF]
f	50 [kHz]

[a] Polarity of V2 depends on the mode of operation (+) for Modes A & B and (-) for Modes C & D.

III. SIMULATION RESULTS

A. *Current behavior for a ±V2 load.*

Fig 5 shows the current I_{L2} in acceleration and braking modes, where, if V2 is positive and current is increased positively, it means that the circuit is trying to get the acceleration state shown in Fig. 2a. Furthermore, if V2 is positive and the current is increased negatively, then it determines positive braking mode as shown in 2b.

For negative acceleration state, V2 is negative and also the current I_{L2} is increased negatively as is shown in 2c and negative braking state is determined by a negative V2 with positively increasing of I_{L2} as is shown in 2d.

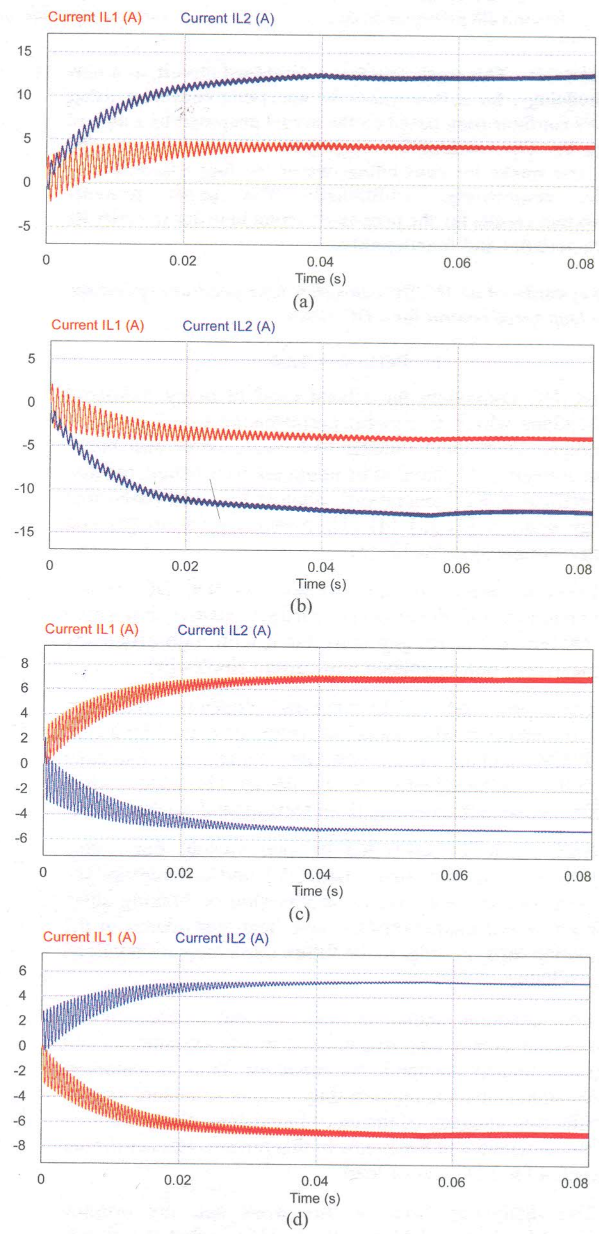


Fig. 5. Current behavior for (a) V2 = +14 [V] at δ = 0.26 (Mode A), (b) V2 = +14 [V] at δ = 0.76 (Mode B), (c) V2 = -14 [V] at δ = 0.26 (Mode C), (d) V2 = -14 [V] at δ = 0.76 (Mode D) [2]

For comparative theorical wave forms refer to [11] [12].

B. Current behavior for a DC motor load.

As shown in Fig. 6, a DC motor is implemented as a load in the output where Ve represents the separately excitation voltage for the motor. Table III shows the motor's parameters considered in the implementation.

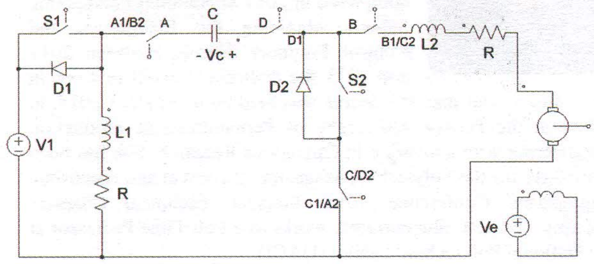


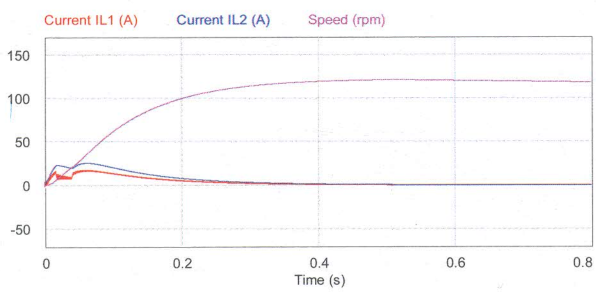
Fig. 6. Combined Luo-converter circuit with a separately excited DC motor load

TABLE III. DC MOTOR PARAMETERS

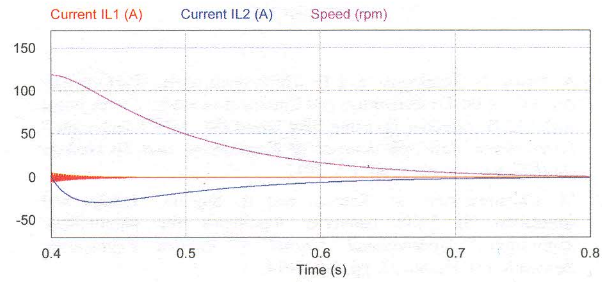
Parameter	Value
Ra	0.7 [Ω]
La	10 [mH]
Rf	75 [Ω]
Lf	20 [mH]
Moment Inertia	0.7 [kgm²]
Vt	120 [V]
Ia	10 [A]
n	500 [rpm]
If	1.6 [A]
Ve	120 [V]

Where, Ra is the Armature resistance, La is the Armature inductance, Rf is the field resistance, Lf is the field inductance, Vt is the Nominal voltage, Ia is the nominal current, n is the nominal speed.

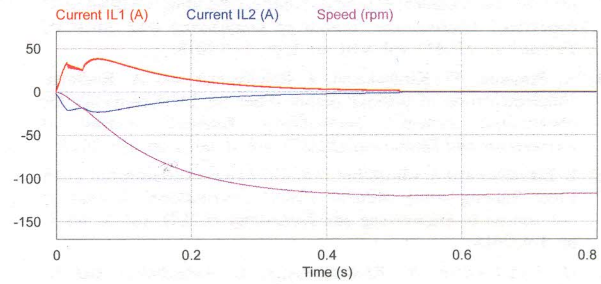
Fig 7 shows the motor speed and the current in the output I_{L2} in acceleration and braking modes with a DC motor load. In purple is shown the motor speed that defines positive acceleration in 4a, brakes positively in 4b, accelerates negatively in 4c and brakes negatively in 4d. Braking is started in t=0.4 because it depends on acceleration state.



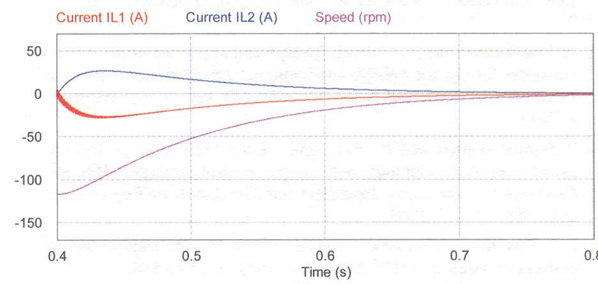
(a)



(b)



(c)



(d)

Fig. 7. Speed output for a (a) motor load with $\delta = 0.40$ (Mode A), (b) motor load with $\delta = 0.99$ (Mode B) at t=0.4, (c) motor load with $\delta = 0.40$ (Mode C), (d) motor load with $\delta = 0.99$ (Mode D) at t=0.4 [13]

Duty cycle values were tested in the experimentation in order to obtain safe operation ranges. It was necessary because overcurrent values could damage the circuit and small values can make the circuit to respond extremely slow, then, the safe duty cycle range was between, $0.30<\delta<0.50$ for acceleration modes and $0.80<\delta<0.99$ for braking modes.

IV. CONCLUSIONS

The proposed combined circuit model for a four-quadrant operation Luo-converter seems to be reliable for controlling a DC motor load in acceleration and braking modes. This is possible due to EMF, as a generating part of the output current increase positively or negatively depending on the operation mode.

The considered parameters for a DC motor make the circuit more reliable for a future implementation considering safe duty cycle ranges in order to protect the circuit integrity and stability. These ranges are, $0.30<\delta<0.50$ for acceleration modes and $0.80<\delta<0.99$ for braking modes.

It is important to consider maximum current values when suddenly changing quadrants, as these could damage circuit elements, e.g. a change from I quadrant to III quadrant over increases the input loop current.

V. References

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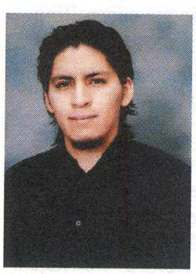
VI. Biographies



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